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# WATERTOWN ARSENAL LABORATORIES

## THE EFFECT OF SPECIMEN GEOMETRY ON DETERMINATION OF ELONGATION IN SHEET TENSILE SPECIMENS

TECHNICAL REPORT NO. WAL TR 111/26


BY

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and

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OMS CODE 4230.1.0000.20
INDUSTRIAL PREPAREDNESS MEASURE - PRODUCT IMPROVEMENT


WATERTOWN ARSENAL
WATERTOWN 72, MASS.

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Tension Testing

Elongation

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TITLE

THE EFFECT OF SPECIMEN GEOMETRY ON DETERMINATION OF ELONGATION IN SHEET TENSILE SPECIMENS


ABSTRACT

The influence of specimen thickness and width on the elongation in 2 in. was studied on copper, AISI 1020 steel, and heat-treated H11 steel.

The results conform approximately to Templin's equation, $El = C\,A^n$. The constant n, a measure of the variation of elongation in 2 in. with specimen area, is shown to be related to the log of the ratio of the zero gage length (fracture strain) to the infinite gage length (uniform strain) elongations. A method is shown for predicting the elongation in 2 in. for a bar of any thickness (or width) from measurements on another bar of the same material. The reason for specimen area being of greater importance than absolute values of width or thickness in controlling elongation is demonstrated by studying the strain distribution near the fracture.

The methods outlined in this report will enable specification and inspection personnel to determine how elongation values will vary with sheet thickness.



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## INTRODUCTION

The current interest in sheet material has emphasized the need for a more accurate understanding of the significance of ductility of materials. This is especially true of elongation, which is the most common, and frequently the only means used for assessing ductility of sheet materials. Unfortunately, elongation values depend on such geometrical factors as specimen thickness and width in addition to gage length and the inherent ductility of the material itself. As a convenience, a constant gage length and specimen width are used as the ASTM standard sheet tensile specimen[1], but this means that the elongation of specimens of different thicknesses are not strictly comparable. If an inter-relationship between elongation, gage length, specimen width, and specimen thickness could be determined, either analytically or empirically, it would be possible to correlate ductility for materials of widely different sizes and shapes.

The goal of this investigation was to develop an understanding of how the specimen geometry affects elongation. It was recognized that the elongation of a tensile specimen can be roughly divided into a uniform strain and a localized strain associated with the neck. Since the extent of the necked region varies with the specimen area, its contribution to the total elongation of a fixed gage length will also vary with specimen area. By applying a grid to the surface of the specimens, the elongation associated with the uniform strain and localized strain can be determined for various specimen geometries. Reported herein are some results on how specimen and thickness affect the elongation in a fixed gage length. The influence of reduced section length (shoulder restraints or stored elastic energy) have been neglected.

## LITERATURE REVIEW

There has been considerable interest in the past in the effects of specimen geometry on tensile properties and especially on elongation. The older European literature has been reviewed in Handbuch der Werkstoffprüfung[2], whereas much of the American literature was reviewed in a recent DMIC report[3].

Quantitative relations between elongation and gage length and/or cross-section geometry generally take two forms:

a. variation of elongation with gage length for specimens of a given cross-section, and

b. variation of elongation with specimen area in specimens with differing cross-section size and/or geometry but with the same gage length.

Equations relating elongation and gage length have been important because of the great number of gage lengths in common use and the desirability of comparing elongation values. Throughout the world, the gage lengths used for determining elongation vary from 3.54 to 10 times the specimen diameter for round specimens (Reference 2), and from 4 to 11.3 times the square root of the area for flat specimens. Even within one country, two or more gage lengths may be used.

These equations generally recognize that the elongation is a maximum for a zero gage length. The zero gage length elongation can be calculated from the true fracture strain or reduction of area. From this maximum value the elongation decreases as the gage length increases, and approaches a limiting value as the gage length approaches infinity. If creep or shoulder restraints could be avoided, this would be the strain at onset of necking, or the maximum uniform strain.

The dependence of elongation on specimen cross-section area has been recognized. This can be seen by the designation of gage length as some multiple of specimen diameter for round specimens. Even for rectangular specimens, gage lengths have been specified as a multiple of the square root of the area. Since the elongation depends on the area and not the dimensions, the cross-section shape is relatively unimportant. Templin reported similar elongation values for variously shaped specimens, including tubular[4], of the same area. Some of the equations relating elongation in a fixed gage length and specimen cross-section area are:

Bauschinger[5] $$El = El_u + \frac{Q}{L}\sqrt{A} \quad \ldots . \text{ (1)}$$

Bertella[6] $$El = C + \frac{1}{Lm} A^m/2 \quad \ldots . \text{ (2)}$$

Templin[4] $$El = C\ A^n \quad \ldots . \text{ (3)}$$

where

$El$ = percent elongation

$El_u$ = percent elongation measured on an infinitely long gage length

$A$ = original area

$L$ = gage length

$C, Q, m, n$ = constants

All three equations show that the elongation increases with some exponential function of the area. Templin's equation does not consider variations in both gage length and area, so the term $El_u$ does not appear.

## MATERIALS AND PROCEDURE

Since contributions to elongation can ideally be considered to come from the two sources, the uniform elongation and the extension associated with the neck, the effect of specimen geometry on these quantities was to be determined. This was accomplished by photogridding the specimens with a grid spacing of 20 to the inch along the reduced section and analyzing the distribution of strain throughout this region, with particular emphasis placed on the necked region. With this in mind, the materials used were selected because of their differences in uniform strain values. The materials used, each of which were individual heats, were hard-drawn copper, annealed copper, AISI 1020 steel, and H11 tool steel. The copper and steel were obtained as 1/2-in.-thick by 2-1/2-in.-wide bars in random lengths and the H11 was supplied in 1/8 in. sheet. After insuring the homogeneity of the material by macroetching and hardness surveys, tensile specimens of various thicknesses and widths were prepared from the 1/2 in. bar by slicing to the approximate thickness and then carefully grinding to size. Specimen thicknesses from 0.010 to 0.500 in. were prepared, with widths ranging from 1/8 to 2 in., see Figure 1. This resulted in specimen width-to-thickness ratios of from 1:1 to 200:1 and areas ranging from 0.0013 to 1.00 sq. in.

Tensile properties of the various materials used are summarized in Table I.

TABLE I

| Material | 0.2% Yield Strength (psi) | Tensile Strength (psi) | Reduction of Area (%) | Elongation Total (%) | Elongation Uniform (%) | Specimen Type |
|---|---|---|---|---|---|---|
| Copper, Hard-Drawn | 34,800 | 37,000 | 69.2 | 30.0 | 7.0 | 0.357 in. diam. |
| Copper, Annealed | 8,900 | 31,000 | 70.4 | 37.9 | 26.5 | 0.357 in. diam. |
| 1020 Steel | 32,300 | 55,900 | 63.0 | 37.1 | 25.0 | 0.357 in. diam. |
| H11 Tool Steel | 231,000 | 250,900 | - | 8.8 | 4.0 | 1/2 in. x 1/8 in. |

The copper was received in the hard-drawn condition. The annealed copper was obtained by annealing the as-received material for one hour at 1200 F. Testing of both coppers was carried out after machining and an anneal of two hours at 400 F. The AISI 1020 hot-rolled steel was normalized at 1700 F prior to machining and annealing at 750 F for 2 hours. The H11 tool steel was machined to size, austenitized in a salt pot at 1800 F for 20 minutes (after preheating at 1450 F), quenched in still air, and tempered twice, 1 hour each time, at 1050 F.

Since the specimens were of various sizes, a good range in load capacities was necessary and three different tensile testing machines were utilized. The head speed of the machines was regulated so that all specimens were strained at an initial rate of 0.01 inch per inch of gage length up to the yield and then at 0.02 inch per inch of gage length to fracture.

All the specimens had been photogridded prior to testing with the grids spaced at 20 to the inch. Grids were put on the width surface for specimen thicknesses of 1/8 in. or less and on both the width and thickness surface for specimen thicknesses of 1/4 in. and 1/2 in., see Figure 2. As shown on this figure, two local strains, namely the width and longitudinal strains, can easily be measured on all specimens and the thickness strain can be measured on the larger specimens. On the thinner specimens the average thickness strains can be measured directly, with a micrometer. Furthermore, any one strain can be calculated from the other two, since because of constancy of volume, the sum of the principal strains is zero.

## RESULTS

The results plotted in Figure 3 show that over a range of sizes, there is a linear relationship between log of elongation in 2 in. and log of area. There is considerable scatter, however, especially at low specimen areas. A consideration of the absolute width and thickness dimensions, or the width-to-thickness ratios, yielded no explanation for the scatter, except that the 0.010 in. and in some cases the 0.020 in. thick specimens tended to show low values of elongation. For a 0.010 or 0.020 in. thick specimen, a variation in thickness of ±0.001 in. would have a great effect in localizing the strain from the very onset of plastic flow. Furthermore, there is the greater chance of damaging these specimens during machining. Many of the elongation values for these thin specimens are lower than the strain at maximum load as determined on standard size round specimens, which suggests that initial dimensional variations caused nonhomogeneous strain.

Three equations mentioned earlier, Equations 1, 2, and 3, relate elongation to some power of the area. It must be realized that for a specimen with an area approaching zero, the elongation approaches the uniform elongation, and for very large specimens, the elongation in 2 in. approaches the zero gage length elongation. None of the equations approach these limits at zero and infinite gage length, which emphasizes their empirical nature. Bauschinger's and Bertella's equations do approach a finite value at zero area, however. In Figures 4a to d are plotted log $(El - El_u)$ versus log area. The uniform elongations were determined from true stress-strain tests. It can be seen that a straight line can be drawn here also, although the scatter is actually greater than shown, since data points for specimens which showed an elongation less than the uniform elongation (as determined from a separate specimen) have negative values of $El - El_u$ and hence are omitted. Since an independent determination of $El_u$ must be made, it seems that no practical advantage is offered over Templin's equation.

## GENERAL DISCUSSION

There are three questions concerning the observed relationship between elongation and area which are of interest. The first is concerned with the greater significance of area, rather than width-to-thickness ratio or reduced section length-to-width ratio, in determining elongation; the second, with the slope of the straight line portions of the curves in Figure 3, which is the exponent "n" in Templin's equation; and the third, with the possibility of predicting elongation values for different size specimens.

### Significance of Specimen Area

Figure 5 shows a plot of the distribution of local elongation of a specimen, measured along the longitudinal axis of the bar over gage lengths of one grid spacing. It can readily be shown that the elongation over a 2 in. gage length can be represented on such a plot by a horizontal line drawn such that the area under it is the same as the area under the curve of local elongation. Figure 5 shows a plot of strain distribution for three bars of the same cross-section geometry, but different areas. The shapes of the curves are generally the same, except that as the specimen area gets larger, the curve gets broader, which is an indication of the larger extent of the necked region. There is an effect of size on the maximum strain. This is caused partially by the difficulty in determining the true zero gage length elongation from measurements made on gage lengths of 0.05 in. minimum, and partially by a true effect of size on fracture strain (zero gage length elongation). Further, the local strain at the extremities of the gage length section is greater for the larger area bar, because of the closer proximity to the neck. All in all, however, the greater elongation in 2 in. (area under the curve) for the larger area bars can be attributed to the larger extent of necked region. Unfortunately, it it not possible to unambiguously separate the uniform strain region from the necked region.

Figure 6 shows similar plots of local strain for three bars having the same area, but different cross-section geometries. Within experimental accuracy, these bars have the same elongation, and hence the same area under the curve. (The 1/2 in. by 1/2 in. specimen fractured close to one of the shoulders, which accounts for the low elongation values of 30.5 percent.) Notice now that the shapes of the curves are quite different. At a width-to-thickness ratio (w/t) of 1, the local strain decreases uniformly with distance from the fracture. As w/t increases, there is a tendency for a more rapid decrease of strain with distance in a very narrow range in the vicinity of the fracture, with a change to a more gradual decrease at larger distances from the fracture. The height of the curve for high w/t ratios is such that at intermediate distances from the fracture it lies below the curve for a square specimen and at large distances from the fracture it lies above, with the net result being the same area under the curve.

Because of the constancy of volume, it is possible to break the longitudinal strains into a component of transverse or width strain and thickness strain. Further insight into the shape of the curves can possibly be found by considering the effect of width-to-thickness ratio separately on width and thickness strains. Some results are plotted in Figure 7, where true strains have been used, since here the sum of the width and thickness strains should equal the longitudinal strain. The width strains were determined over a one-grid length (0.05"), whereas the thickness strains were determined over the whole thickness.

The results clearly show the differing behavior for the various w/t's. For a w/t of 1, the width and thickness strains are almost equal. (The hard-drawn copper is actually slightly anisotropic, by virtue of having a preferred orientation arising from cold working.) As w/t increases, there is a restraint in the width direction, and the ratio of the thickness strain to the width strain increases at the fracture, so that most of the elongation at this point arises from the contribution of the thickness strain.

## Significance of Exponent "n" in Templin's Equation

Of some importance is the slope of the curves in Figure 3, which is characterized by the exponent "n" in Templin's equation, Equation 3. The importance of this lies in the fact that it is a measure of the sensitivity of elongation values to thickness changes. It would tell, for example, whether two materials which have the same elongation value at a thickness of 1/8 in. would also have the same elongation at some other thickness. One is tempted to look upon the exponent "n" as a material property, which can be determined and tabulated. A little reflection on the problem will show the fallacy of such an approach.

Since the length along the specimen occupied by the neck is proportional to the specimen cross-section area, the elongation in two inches would be simply the maximum uniform strain for a bar of infinitely small area (assuming homogeneous deformation until maximum load). Similarly, for a bar of infinite cross-section area, the elongation in two inches approaches the zero gage length elongation, which can be calculated from the reduction of area or fracture strain. The zero and infinite gage length elongations therefore define the upper and lower limits respectively of a log-log plot of elongation in two inches versus specimen area.

In order to show the importance of zero gage length elongation in controlling the elongation-area curve, this maximum strain was reduced, maintaining the uniform strain constant. This was done by pulling a series of AISI 1020 steel bars of different areas to a true strain at the neck of 0.5. The elongation in two inches was measured, and is plotted in Figure 8 together with the line for the bars pulled to fracture. It can be seen that the slope is reduced by reducing the maximum strain to 0.5. This can more strikingly be visualized by considering bars which fracture at strains less than the uniform strain, before necking has started. In such a case, the elongation is independent of gage length and specimen area, and the data would appear on a plot such as Figure 8 as a horizontal line with a slope of zero.

Although the fracture and uniform strain define the upper and lower limits of elongation, the actual data would probably form a $\int$ curve. Over the range of areas of practical interest a straight line can probably approximate the data. To a first approximation the slope of this line, the constant "n" in Templin's equation, would be proportional to the difference between the logs of the zero and infinite gage length elongations (fracture and uniform strains), and hence to the log of the ratio of these elongations. This quantity for the various materials is tabulated in Table II, together with the slopes "n" from Figures 3 and 8. The zero and infinite gage length elongations were obtained from the reduction of area at fracture and the strain at maximum load for 0.357 in. round specimens (Table I), except for the H11, where the zero gage length elongation was calculated from the sum of the width and thickness strains of a 1/2 in. x 1/8 in. specimen.

TABLE II

| Material | Zero Gage Length Elongation, $El_o$ | Infinite Gage Length Elongation, $El_\infty$ | $El_o/El_\infty$ | $\log El_o/El_\infty$ | Templin's Exponent "n" |
|---|---|---|---|---|---|
| AISI 1020 Steel, strained to 0.5 | 65 | 25.0 | 2.6 | 0.41 | 0.14 |
| AISI 1020 Steel, fractured | 170 | 25.0 | 6.8 | 0.83 | 0.18 |
| Copper, annealed | 238 | 26.5 | 9.0 | 0.95 | 0.16 |
| Copper, hard-drawn | 225 | 7.0 | 32.0 | 1.51 | 0.23 |
| H11 Tool Steel | 63 | 4.0 | 15.7 | 1.20 | 0.30 |

The results do show a rough correlation between the log of the ratio of these elongations and the slope. There are many assumptions made in this analysis which must be considered. First, it has been assumed that the slope of the actual $\int$ curve is proportional to the difference between the maximum and minimum values. Furthermore, it is assumed that the zero and infinite gage length elongations are independent of specimen dimensions. In addition, there are experimental difficulties in determining the zero and infinite gage length elongations. A small change in the infinite gage length elongation can cause an appreciable change in the log of the ratio.

In spite of the crudeness of the analysis, it does point out some useful trends. From these considerations, it can be seen that the exponent "n" in Templin's equation is not a general material property which can be tabulated, but rather depends on the ductility of the specific lot of material being tested. For two different materials with the same uniform strain, the one having the higher fracture strain would have the greater value of the exponent "n". Similarly, for a constant fracture strain, the lower the uniform strain the higher the value of this exponent. Unfortunately, the high-strength sheet materials of current interest do have a low value of uniform strain with moderate fracture strains, so that their elongation values are quite sensitive to variations in thickness (area).

## Prediction of Percent Elongation

In many cases, it would be desirable to be able to predict the elongation for any arbitrary size specimen. Lacking complete data for many specimens which would allow an interpolation to be made, there is a method which suggests itself. This is based on the concept that a constant elongation is obtained if $\sqrt{A}/L$ is maintained constant, as suggested by Bauschinger's equation, Equation 1. This concept is inherent in maintaining a gage length to diameter ratio of 4 for round tensile specimens, and in the practice used abroad of defining gage length as a constant multiple of the square root of the area. Malmberg[7] found this to be valid for round bars, but not for rectangular bars. The results of this investigation support Malmberg. Nevertheless, under some conditions it is a good approximation for rectangular bars. If it is valid, then at a constant value of elongation:

$$\frac{L_1}{\sqrt{A_1}} = \frac{L_2}{\sqrt{A_2}}$$

where L and A are the gage lengths and area of two different bars, 1 and 2. To determine the elongation in length $L_2$ on a bar with an area $A_2$ from measurements on a bar with area $A_1$, simply measure the elongation on bar 1 over a gage length $L_1 = L_2\sqrt{\frac{A_1}{A_2}}$. From this relation, the elongation in a fixed gage length for any area bar can be calculated from measurements over different gage lengths on one bar.

Some results using this method have been calculated for several size bars of the various materials, and are plotted in Figure 9 with the experimentally determined results from Figure 3. In some cases, the points do not lie on the experimentally determined curve, since the standard 2-inch elongation for the bar used lies off the curve. In general the results are good, and the slopes of the experimental and calculated curves are the same. Deviations are noted when the elongation must be measured over such a long gage length that either a second necked region or end restraints are encountered.

In a practical sense, this principle could be applied to standard 1/2-in.-wide specimens. Suppose, for example, one had available and knew the properties of 1/8-in. sheet. What elongation would be expected in sheet 0.080-in. thick? From the above relation, one can determine that the elongation measured on $L = 2\sqrt{\frac{.125}{.080}} = 2.5$ in. of the 1/8-in. sheet is the same as the elongation in 2 in. in 0.080-in. sheet. Accurate values should be obtained if the areas do not differ appreciably.

## SUMMARY

A study has been made of the effect of specimen width and thickness on the elongation in 2 in. as determined in a sheet tensile test. Hard-drawn copper, annealed copper, AISI 1020 steel, and H11 tool steel were studied.

The elongation in 2 in. is found to vary approximately linearly with the specimen area on a log-log plot, showing agreement with Templin's equation, $El = C\ A^n$. The reason for the greater dependence of elongation on specimen area, rather than width-to-thickness ratio, can be seen from a study of the local width, thickness and longitudinal strains.

The sensitivity of elongation to specimen area or thickness, as measured by the exponent "n" in Templin's equation, is dependent on the fracture strain as well as the uniform strain, and hence varies from heat to heat of material. This exponent has been related to log of the ratio of the zero gage length (fracture strain) to infinite gage length (uniform strain) elongations.

If $L/\sqrt{A}$ is maintained constant, the elongation will be approximately constant. Using this relation, it is possible to estimate the elongation for any size bar from measurements made on one bar.

The methods outlined in this report will enable specification and inspection personnel to determine how elongation values will vary with sheet thickness.

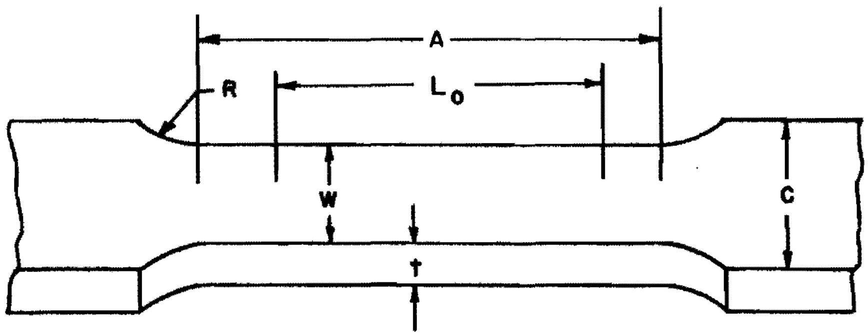



FIGURE I

<u>WHERE</u>

W: 1/8", 1/4", 1/2", 1", 1-1/2", AND 2"

t: 0.010", 0.020", 0.040", 0.080", 0.125", 0.250", AND 0.500"
(IN NO CASE WAS W/t < 1)

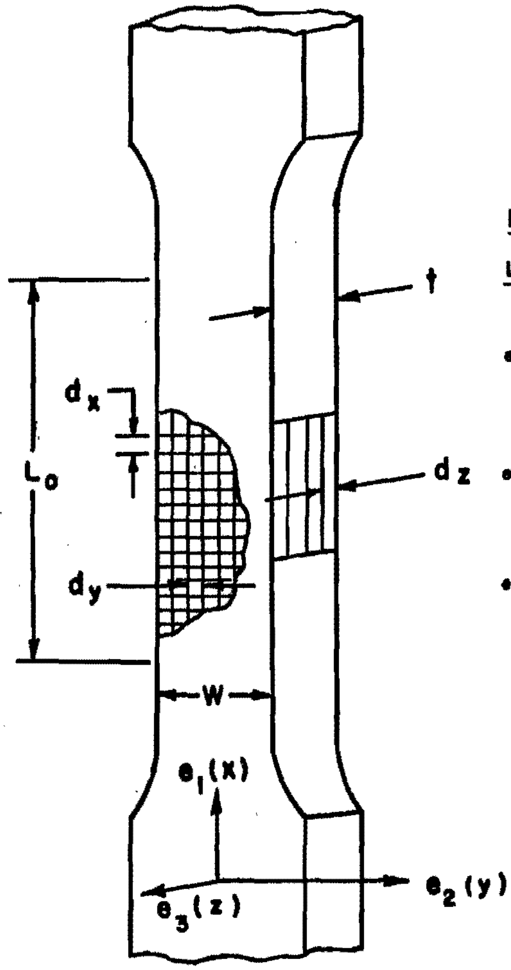
C: 1/2" FOR W = 1/8" AND 1/4", 1" FOR W = 1/2", 2" FOR
W = 1", AND 2-1/2" FOR W = 1-1/2" AND 2"

R: 1" RADIUS IN ALL CASES

$L_o$: 11.3 $\sqrt{Wt}$, BUT MINIMUM 2"

A: $L_o$ + 2W

## FLAT TENSILE SPECIMEN



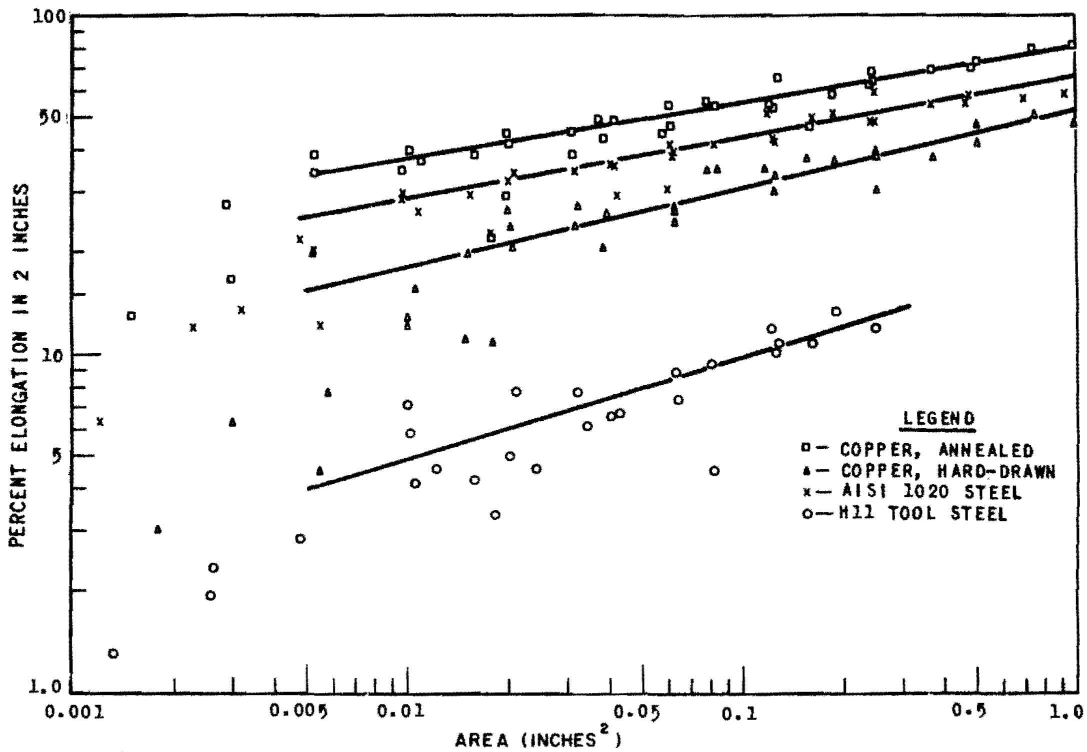

**RELATIONS:**

| LOCAL STRAINS: | AVERAGE STRAINS: | WHERE: |
|---|---|---|
| $e_1 = \frac{d_x' - d_x}{d_x}$ | $e_1 = \frac{L - L_o}{L_o}$ | $d_x'$, $d_y'$, $d_z'$, L, W, and t are the strained values of $d_{x_o}$, $d_{y_o}$, $d_{z_o}$, $L_o$, $W_o$, and $t_o$ |
| $e_2 = \frac{d_y' - d_y}{d_y}$ | $e_2 = \frac{W - W_o}{W_o}$ | |
| $e_3 = \frac{d_z' - d_z}{d_z}$ | $e_3 = \frac{t - t_o}{t_o}$ | |

STRAIN DIRECTIONS IN TENSILE SPECIMEN



FIGURE 2




EFFECT OF SPECIMEN AREA ON ELONGATION IN 2 INCHES



FIGURE 3

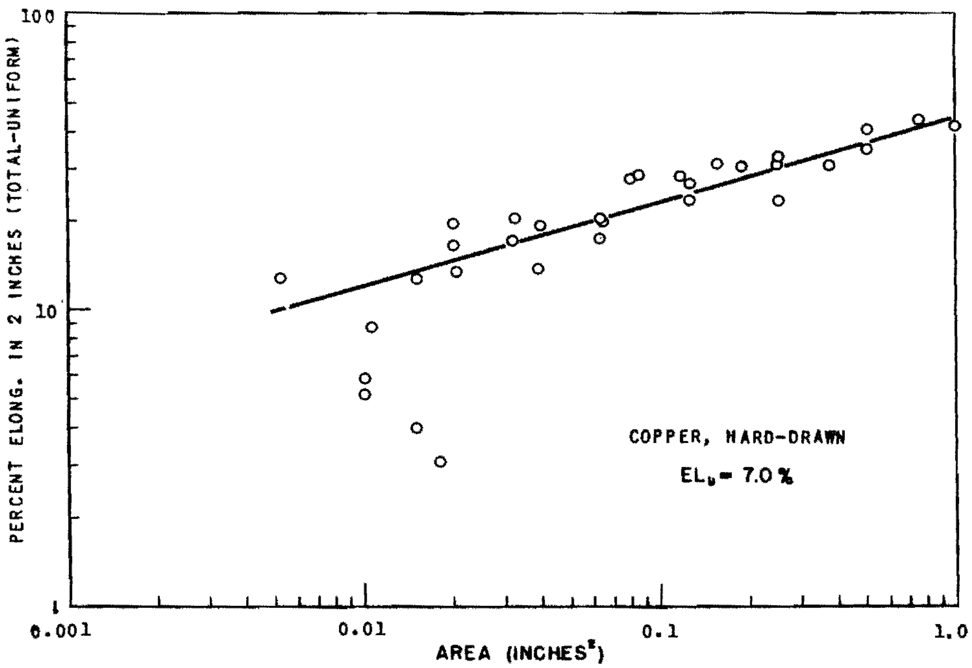



FIGURE 4A

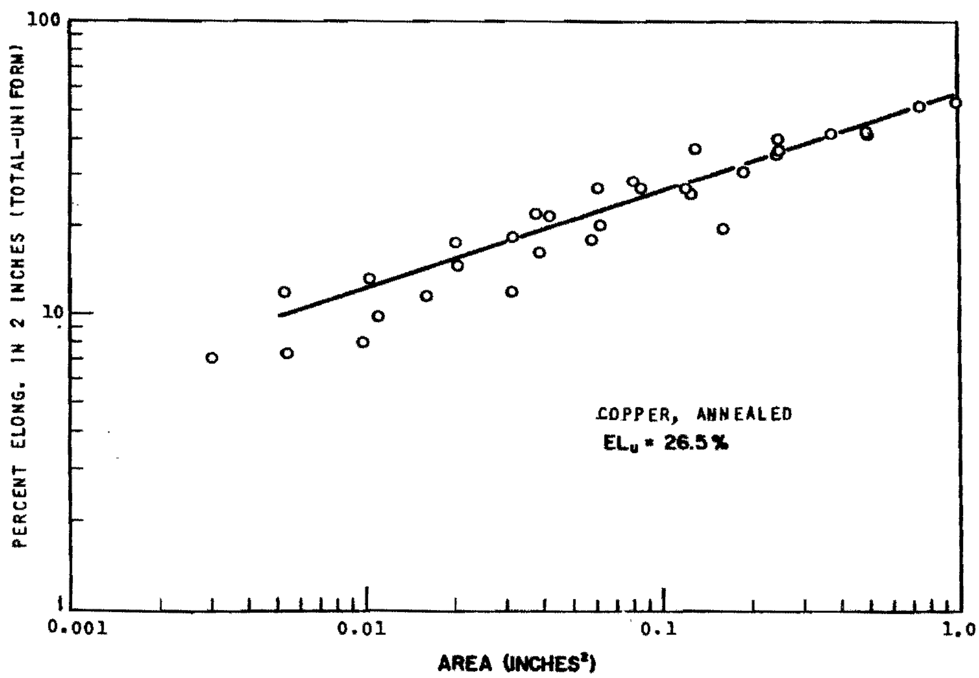



FIGURE 4B

EFFECT OF SPECIMEN AREA ON TOTAL MINUS UNIFORM ELONGATION

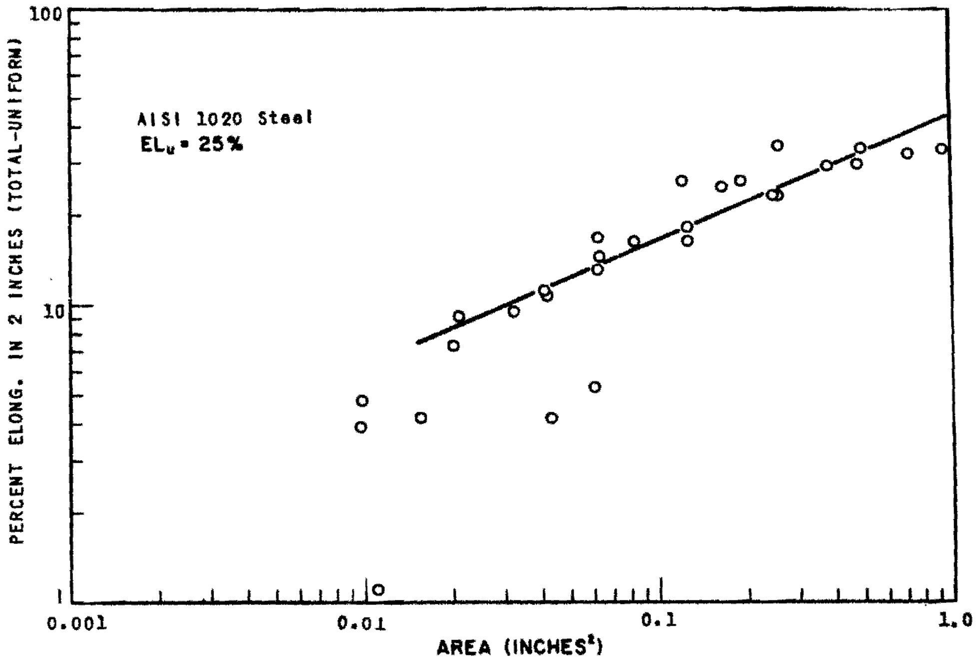



FIGURE 4C

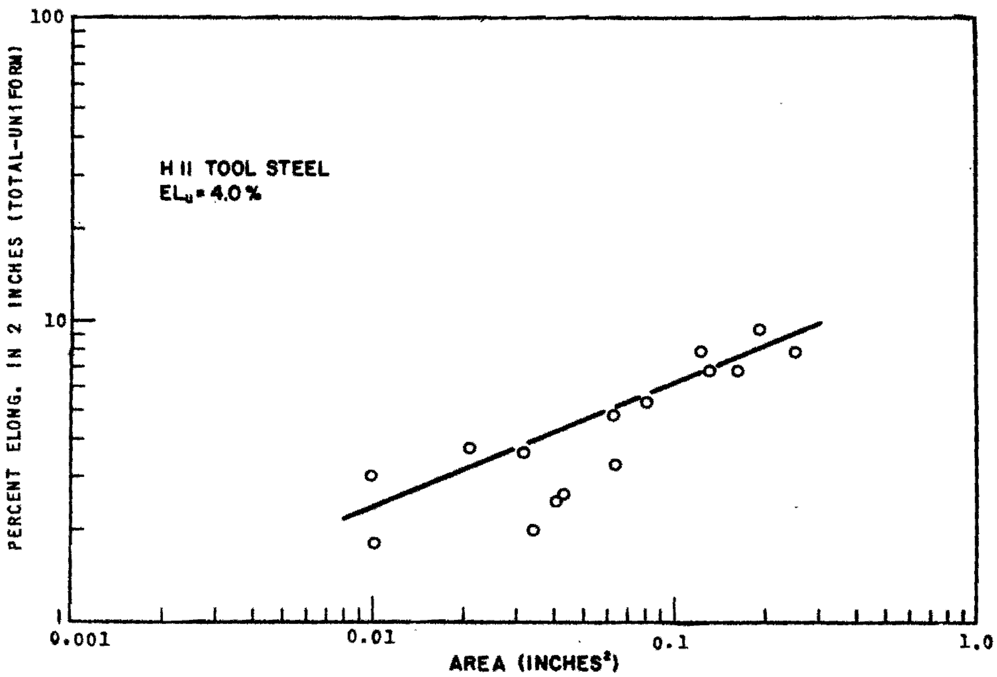
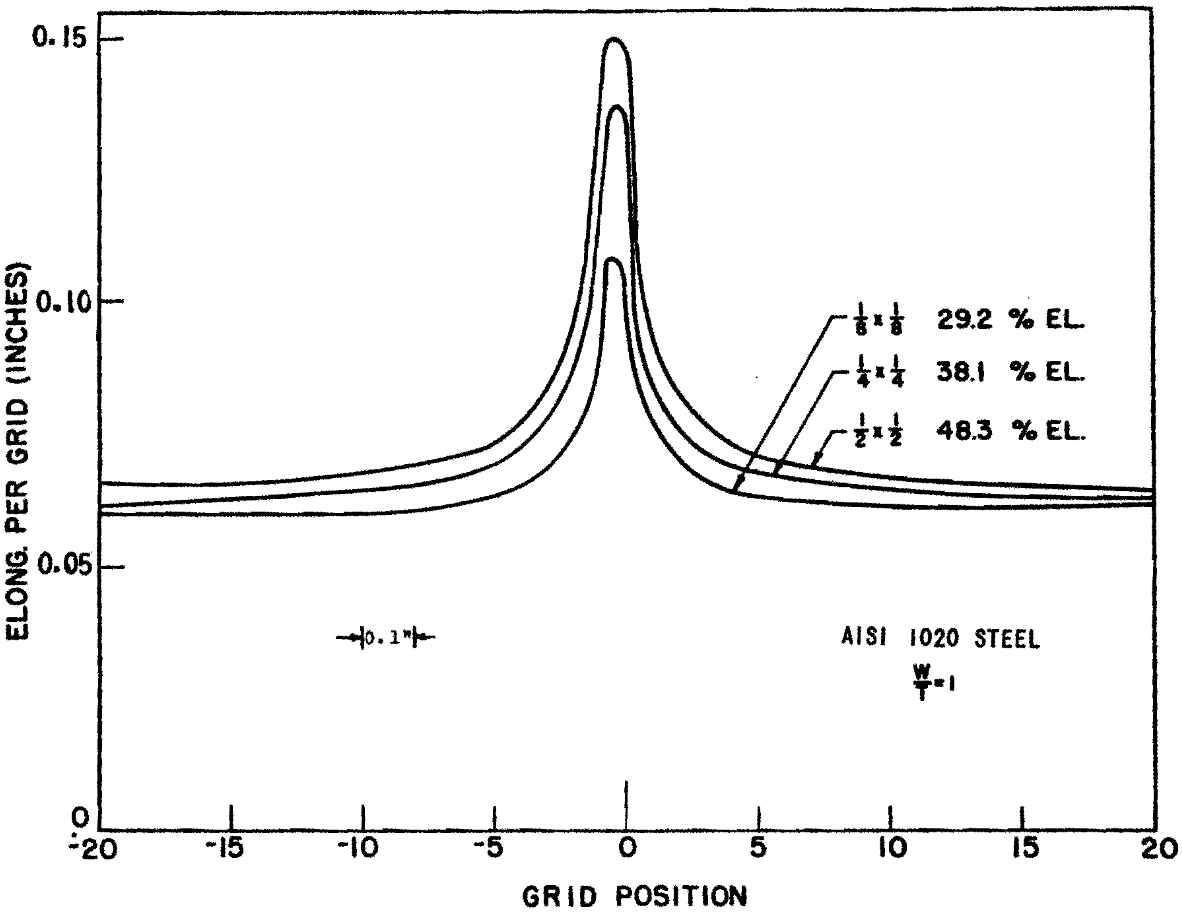



FIGURE 4D

EFFECT OF SPECIMEN AREA ON TOTAL MINUS UNIFORM ELONGATION




LONGITUDINAL STRAIN DISTRIBUTION IN GAGE LENGTH SECTION FOR BARS OF DIFFERENT AREA



FIGURE 5

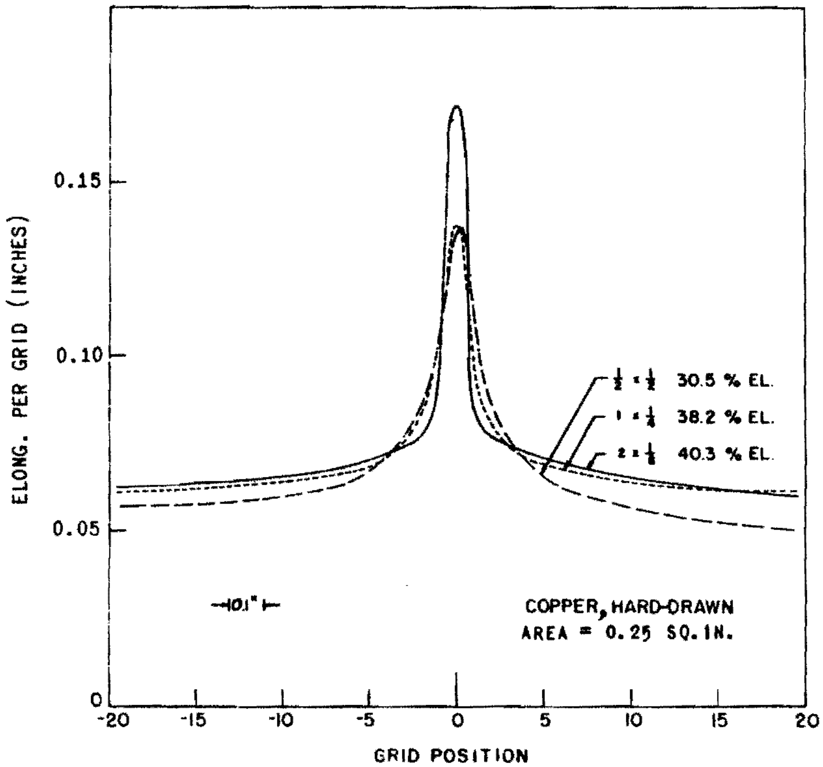



**FIGURE 6: LONGITUDINAL STRAIN DISTRIBUTION IN GAGE LENGTH SECTION FOR BARS OF SAME AREA BUT DIFFERENT GEOMETRY**

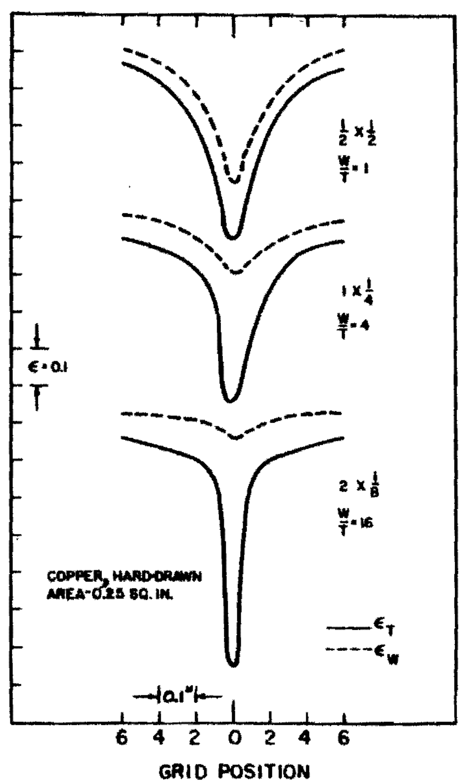



**FIGURE 7: WIDTH AND THICKNESS STRAIN DISTRIBUTION IN GAGE LENGTH SECTION FOR BARS OF SAME AREA BUT DIFFERENT GEOMETRY**

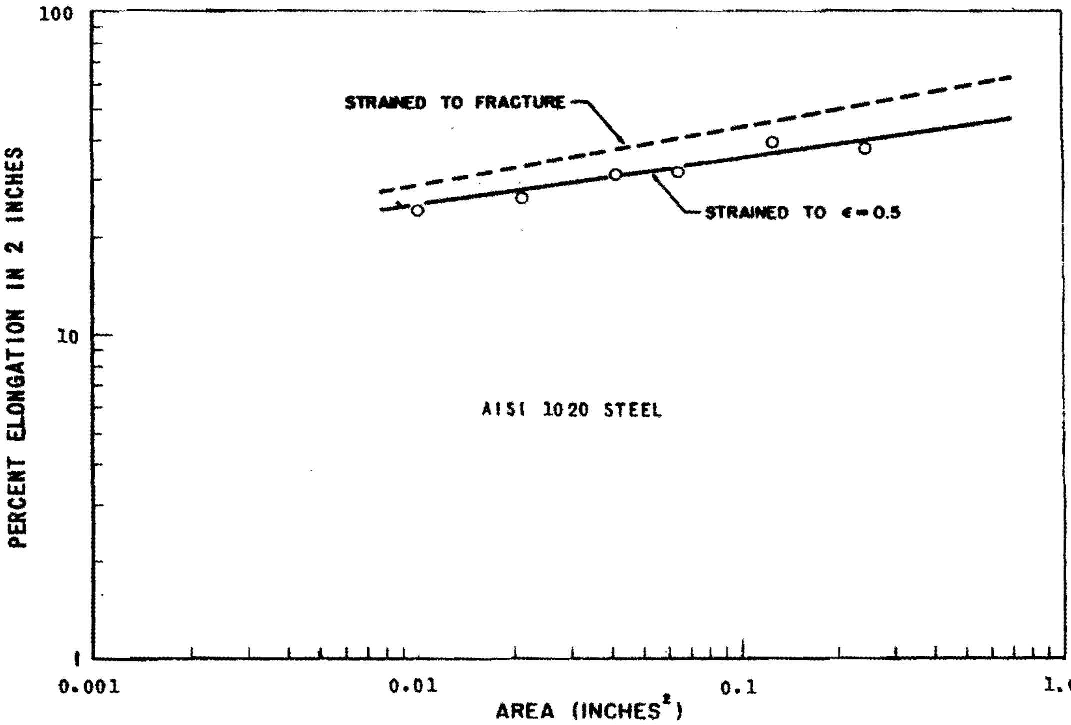



FIGURE 8: VARIATION OF ELONGATION IN 2 INCHES WITH SPECIMEN AREA

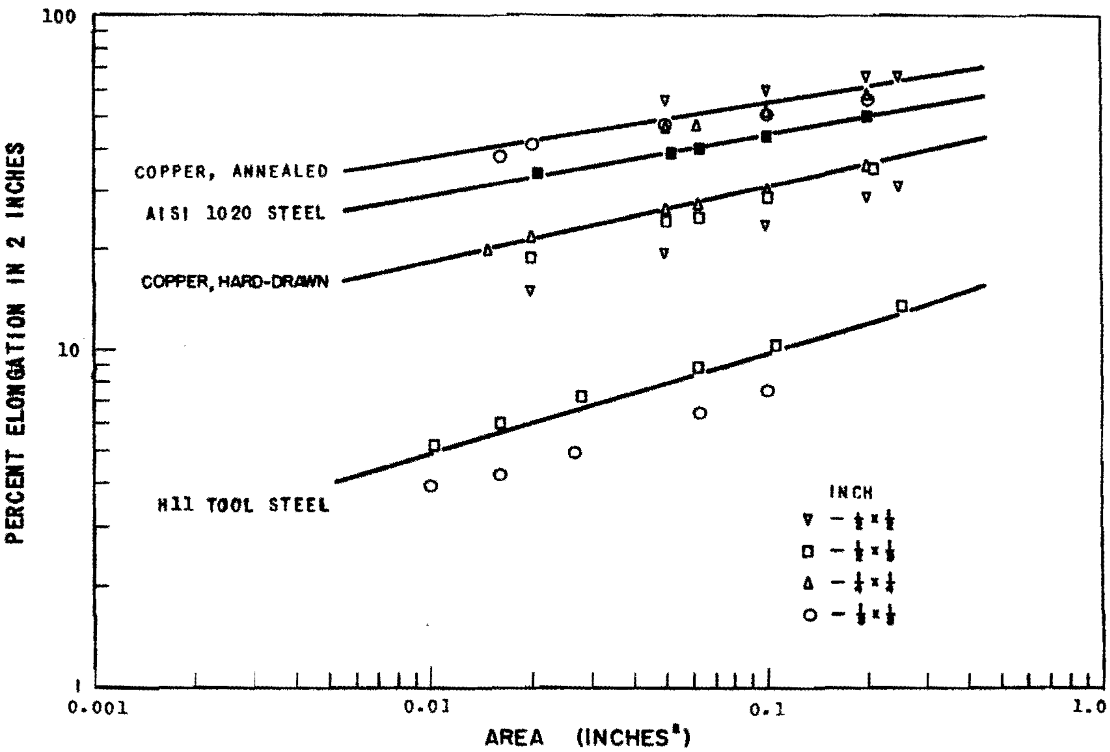



FIGURE 9: CALCULATED VARIATION OF ELONGATION IN 2 INCHES WITH SPECIMEN AREA

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Report No.: WAL TR 111/26 Title: The Effect of Specimen Geometry on Determination of Elongation in Sheet Tensile Specimens
May 1961

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